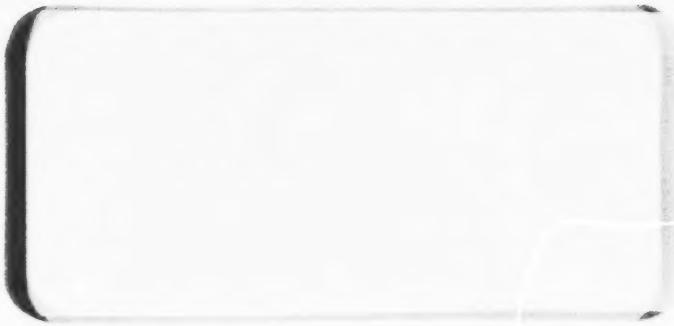
Technical Report



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WELD PROCESS DEVELOPMENT FOR [redacted] WALL PRESSURE VESSELS. PART 1

BY

B. Wright

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WELD PROCESS DEVELOPMENT FOR FABRICATION OF HEAVY WALL PRESSURE VESSELS. PART 1

BY

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ABBREVIATIONS

AC	Alternating Current
BHN	Brinell Hardness Number
DC	Direct Current
EGW	Electrogas Welding
ESW	Electroslag Welding
EBW	Electron Beam Welding
FATT	Fracture Appearance Transition Temperature
FCAW	Flux Cored Arc Welding
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
ISR	Intermediate Stress Relief
MT	Magnetic Particle Examination
NDE	Non-Destructive Testing
N-MIG	Narrow Gap Gas Metal Arc Welding
N-SAW	Narrow Gap Submerged Arc Welding
PWHT	Post Weld Heat Treatment
PT	Dye Penetrant Examination
RT	Radiographic Examination
SAW	Submerged Arc Welding
TTR	Transition Temperature
UT	Ultrasonic Inspection

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1.0 SUMMARY

The manufacture of a heavy wall reactor vessel has been detailed to identify improvements in welding technology required by Canadian manufacturers to compete in the fabrication of petrochemical process equipment. Narrow groove welding using the submerged arc process for circumferential seams and electroslag welding of longitudinal seams in formed plate fabrications were identified as profitable development areas. Available narrow groove submerged arc welding systems have been reviewed and the ESAB HNG system selected as the basis for procedure development. Selected equipment was purchased, erected and commissioned in a laboratory environment.

Developments in the 2¼ Cr-1Mo technology have been reviewed; chemical restrictions and thermal treatment practices were identified to ensure that present equipment requirements can be attained. Electroslag welding technology has been reviewed as applicable to heavy section 2¼ Cr-1Mo weldments and further development work is recommended.

2.0 INTRODUCTION

The design of pressure vessels for processing fuel from conventional, tar sands and coal conversion resources, presents an unprecedented challenge to Canadian manufacturers. The heavy section material requirements and the size of the vessels renders ineffective the successful conventional processes employed for manufacturing section thicknesses to 100 mm. Whilst welding of very thick section vessels is a new requirement for Canadian fabricators, the nuclear programs of the U.S.A., U.S.S.R. and Europe have posed similar problems of size and considerable development work has established electroslag, narrow groove and electron beam welding processes as viable alternatives to shielded metal arc and submerged arc methods. Welding heavy pressure vessel walls demands productivity improvement and the assurance of stringent quality levels so that process control and automation find increased significance in an area where operator skill has been of high priority.

The second challenge to pressure vessel manufacturers is the material selected for high temperature processing operations. Fabricating 2¼ Cr-1 Mo steel by conventional processes requires specific attention from welding and production engineers to avoid problems arising from the materials high hardenability. Additionally, the arduous material specifications for strength, toughness and temper embrittlement resistance demand additional attention to material composition, welding parameters and thermal processing.

The aims of the present program are to define the requirements of a welding system from a manufacturing stand-point, select the system compatible with production and metallurgical requirements and commission the hardware. The equipment is then employed to define a procedure specification capable of consistently producing the mechanical and soundness criteria required by process plant design.

3.0 MANUFACTURING OUTLINE FOR REACTOR VESSEL

3.1 Approach to Manufacture

To identify the manufacturing requirements for a system to weld heavy section 2¼ Cr-1 Mo steel, a fabrication review was undertaken for a reactor vessel defined by the descriptions in P.M.R.L. Report (79-85 OP-J), see Table 1. The options for manufacturing the vessel shell courses in Canada were:

3.1.1 Procure machined forgings to ASME SA 336, F22, in the quenched and tempered condition which restricts Canadian content to cladding the inside surfaces and subsequently welding circumferential seams, nozzles and internals. Forged rings 4m long are available from Japan; a reactor shell would be comprised of five courses.

3.1.2 Purchase ASME SA 387, Gr22 plate in the as-rolled and tempered condition and hot form the shell courses. 2¼ Cr-1 Mo plate is currently available from 66t single heats at a width of 3m for the defined pressure vessel. With facilities available to hot form plate of this size, a reactor shell would comprise eight courses and the Canadian content would be increased to include hot forming, welding and the associated NDE of 21m of longitudinal seams, re-rounding, quenching and tempering prior to assembling the shell courses.

3.1.3 The option of cold forming plate into shell courses with an intermediate heat treatment to restore material ductility has been considered but abandoned since cold rolling equipment is not commercially available.

A manufacturing plan for both the hot formed plate and forged ring options was prepared and a review of the manufacturing options is outlined below in paragraphs 3.2 and 3.3.

3.2 Manufacturing Outline for a Formed Plate Fabrication:

To allow for hot forming allowances, ordered plate dimensions would be 3m wide x 13m long and 205mm minimum thickness requiring a plate weight of approximately 64.5t. The accuracy with which plate edges can be brought together during forming depends upon the skill of the roll operator, uniform cooling of the plate and uniform plastic deformation during rolling. For a 205mm thick plate, a mis-match of approximately 10mm is expected. This mis-match is reduced with equipment capable of cold-springing the longitudinal weld joint into accurate alignment prior to welding.

Longitudinal seams in each shell course are welded using conventional submerged arc process. A more efficient method of welding would be to utilize the electroslag process. The coarse grain weld metal and heat affected zones would be recrystallized during the quench and temper operations necessary to develop the plate properties.

Hot formed shell courses will show an out-of-roundness of approximately one percent. The welded shells will therefore require reheating to the hot forming temperature and reforming to limit out-of-roundness to 6mm. The formed cylinders will be reheated for quenching and subsequently for tempering. This approach to manufacture requires that the welding procedures for longitudinal seams be qualified to withstand quenching, tempering and subsequent postweld heat treatment cycles. Each shell course will be sandblasted on the inside and outside circumferences to remove high temperature scale and locally ground to improve longitudinal weld profile. Circumferential weld preparations will be machined at each end using vertical boring mills.

Subsequent processing of these shell courses will be as described under the Manufacturing Outline for forged ring courses in paragraph 3.3.

3.3 Manufacturing Outline for Forged Ring Shell Courses:

Japan Steel Works Ltd.(31), describes capacity to produce seamless ring forgings 4m long for the described reactor vessel without special tooling. The forging process involves cogging and upsetting the ingot followed by punching and mandrel forging on a 10,000 ton press. The forging is heat-treated and rough machined to required dimensions. Similar capability is described by Kobe Steel Ltd. with an 8,000 ton press. The maximum sizes for seamless ring forgings from Japan are described as 10m O.D., 4.5m long and 280 ton weight (as forged).

The inside surface of each shell course (or forged ring) will be strip clad with stainless steel. The deposition of stainless steel will be interrupted at the areas identified for the nozzles so that nozzle openings can be gas cut and machined to the required weld preparation profile. Nozzle to cylinder welds are buttwelds to simplify weld design and to facilitate NDE.

Concurrent with the manufacture of the shell courses will be the sub-assembly of hemispherical heads. These items are procured as two matching halves from pressed plate in the quenched and tempered condition. Welding the longitudinal seam in the head, nozzle to head welds and strip cladding of the head and nozzles follow the same sequence of operations as described for the cylinders.

A complete vessel of the described dimensions exceeds existing railway weight limitations. A limited review indicates that shipment of the vessel in 2 halves is conceivable using 2 eight axle cars with ballast or frame to reduce the centre of gravity below 2.5m. Shop manufacture of the reactor vessel is thus conceived as two sub-components with a closing seam to be completed at site at approximately the vessel mid-length.

Based upon the described manufacturing sequence, the number of intermediate and final post weld heat treatment cycles is summarized as:

3h minimum to 10h maximum 620°C ISR
4h minimum to 20h maximum 690°C PWHT

3.4 Preferred Approach to Manufacture:

The results of a comparative estimate show that manufacture of reactor shells from plate represents a manufacturing cost saving of 5-10% compared to the forged ring approach. Forged rings show greatly improved roundness tolerances compared to formed plate shell sections and reduce manufacturing risks associated with seam welding and strip cladding. However a forged ring approach has restricted application in Ontario where rail transportation limits the import of forgings to 4.3m maximum diameter. The incidence of hydrogen disbonding of stainless steel cladding from reactor vessels during service has been reported from vessels manufactured from forgings and demands review of strip cladding parameters to prevent occurrence.

Pressure vessels of the defined dimensions do not exceed the capability of Canadian hot forming facilities. Vessels of smaller diameter may exceed this capacity since hot rolling is then restricted by thickness to an uneconomical plate width and available plate sizes cannot be hot formed (Fig. 1). To realize the potential savings offered by plate involves significant capital expenditure, payback for which may not be supported by current market projections. Budgetary estimates indicate capital costs of approximately $3.3m to support an efficient production from plate with general costs of $0.7m to upgrade plant common to either option.

Neither plate nor forgings of the required material or size can be procured in Canada and the preferred approach to vessel fabrication would be to maximize Canadian content by the use of hot-rolled plate.

4.0 DEFINITION OF WELDING SYSTEM REQUIREMENTS

4.1 Weld Joint Design:

A comparison of manufacturing times for circumferential seam production using conventional submerged arc welding, narrow groove submerged arc welding (N-SAW) and narrow groove gas metal arc welding (N-MIG) has been made using in-plant and manufacturers' productivity data for each weld process. The results are shown in Table 2 for the machined weld preparations shown in Figure 2. The cost saving by the use of a narrow groove welding techniques is greatest for N-SAW and reflects a reduction in welding time and weld consumable costs. Figure 3 shows that the magnitude of cost reductions (welding time and consumable costs) increases significantly with shell thickness above 200 mm.

Increased savings are shown by the use of a single sided weld preparation using a backing bar. A single sided weld preparation offers further advantages for circumferential seams since joint preparation by flame-cutting is possible, welder discomfort from the 205°C preheat temperature is reduced, the welding operation is completed in one manufacturing cycle and the need for an MT technique in narrow grooves after back grinding is eliminated.

For longitudinal seams in hot formed plate a single sided weld poses problems of final joint preparation where the joint gap is more controlled by the accuracy of forming the plate than by grinding or machining the groove. Furthermore, fitting the backing bar cannot be accurate at the curved inside surface.

4.2 Weld Groove Tolerances:

A single bevel with a 1 to 2° side wall allows the use of flame-cutting or machining for joint preparation. Removal of trim material from a formed plate precedes machining such that cost reductions may be maximized by flame cutting of circumferential preparations for plate shell courses. An accuracy of ±1.6mm along a gas cut edge is to be expected with angular tolerances of ±½°. The incidence of a 0.4mm deep, 1.6mm radius at the top edge would favour gas cutting from the O.D. to minimize weld defects within the groove. Weld preparation with a horizontal boring mill produce machined grooves to accuracies of 0.4mm and ± ½° degree. These tolerances apply to single-sided welds and double U-grooves.

Removal of defects within the groove as welding progresses requires that grinding wheels are able to reach the root of the groove. Grinding wheels are available at 8mm thickness and 510mm diameter which sets the minimum groove width at 10mm and the maximum groove depth at 240mm. The upper limit to groove width reflects manufacturing tolerances, the adopted philosophy to narrow groove welding i.e. single pass or double pass per layer, as well as the process adopted (N-SAW or N-MIG), heat input and the most economical wire diameter.

Variations in weld gap and root mis-match is ±1mm for machined shell courses which exhibit a maximum difference in diameter of 3mm. Mis-alignment caused by machining and fit-up tolerances is thus ± 4mm. Shells manufactured from formed plate show an ovality of 6mm to produce a total misalignment of ± 7mm.

Non-levelling, non-aligned rotators allow cylindrical sections to drift up to 12mm per revolution. With an anti-drift mechanism and aligned rotating rolls this drift is minimized eliminating the need for horizontal guidance over a wide range for both flamecutting and circumferential seam welding.

4.3 Preheat:

To prevent hydrogen related welding problems, preheat of 205°C is applied to 2¼ Cr-1Mo materials. To effectively attain and maintain this temperature during welding and until ISR requires sufficient gas or electric preheat with associated insulation. The system is required to incorporate electric preheat capability for rotating components with the ability to attain low temperature post weld heat treatment and ISR temperatures.

4.4 Operator Control vs. Automation:

Experienced operators produce seams in materials requiring low preheat temperatures by conventional submerged arc welding using essentially visual control of bead placement. Higher preheat leads to welder discomfort and automatic control of arc location is preferred.

To minimize repair costs, the system is required to control side wall fusion and contact tip to work distance (two-axes guidance) from the root to capping pass to compensate for groove width irregularities and to maintain continuity of operation over previously deposited weld metal. A visual description of the groove or a continuous defect monitoring system is required so that the operator can repair defective material prior to completing the weld. Wear of the contact tip and nozzle are to be monitored to predict interruptions during seam welding. Safety factors are to be included to produce a shut down of the complete system without producing defective weld metal.

4.5 Weld Consumables:

Shielding gas or flux feed systems are required to be air tight to prevent ingress of moisture or other contaminants and thus to maintain optimum toughness and soundness. Slag and dross are to be self removing to allow continuity in welding. Filler wire and flux or gas are required to be supplied with minimum interruption which implies the use of automated wire supply, a gas distribution system and/or a flux recovery/feed system.

4.6 Non-Destructive Examination

Process equipment specifications require that pressure boundary weldments be ultrasonically examined in addition to the mandatory radiographic examination required by ASME Boiler & Pressure Vessel Code, Section VIII, Division 1. (Ultrasonic examination is mandatory to ASME Section VIII for electroslag weldments). Conventional ultrasonic inspection using 45° and 60° angle probes does not guarantee detection of sidewall defects i.e., lack of fusion in parallel sided grooves, and a tandem probe method of examination is necessary if laminar defects perpendicular to the surface are to be detected. This method will be incorporated into the examination program for procedure qualification test plates.

4.7 Summary of Welding System Requirements:

The welding process selected for manufacturing heavy section 2¼Cr-1Mo vessels may not be the same for circumferential seams as for longitudinal seams which benefit from application of electroslag welding procedures. At section thicknesses of 200mm, significant reduction in manufacturing costs results from the use of a narrow groove welding process compared to conventional submerged arc welding.

For circumferential seams, cost efficiency is furthermore a function of improving material handling aspects of manufacturing. Automated positioners and rotators which facilitate joint setup, alignment and prevent seam drift during rotation will significantly reduce setup times. Rigid manipulators and gantries to minimize external variables introduced to the welding operation will reduce the complexity of process automation. Flamecut weld preparations can impose extra demands but offer economies during operations which precede welding.

Automation of the welding process including guidance, flux-feed, flux recovery and semi-continuous wire supply to reduce labour costs and increase arc time.

5.0 DEVELOPMENTS IN AVAILABLE WELDING SYSTEMS

5.1 Literature Review:

A literature review to search developments in heavy section welding systems, narrow groove welding, joint tracking has used Compendex, Weldasearch and Metadex information retrieval systems and a bibliography of literature published since 1979 is listed in Section 8.0.

5.2 Welding Centre Concept:

European pressure vessel manufacturers address problems of component fit-up ovality, drift and other external factors prior to welding (1)(2)(3)(4). Their approach has been to establish welding stations employing rigidly built support systems and anti-drift mechanisms with or without self-correcting roller-beds to ensure alignment. The welding centres produce circumferential and longitudinal seams using automatic guidance systems with operator aids such as air-conditioned control rooms and visual groove monitoring. The centres also include facilities for joint preparation, back grinding, slag removal and flux recirculation. Such permanent equipment is in contrast to North American facilities where versatility of application requires support equipment to be semi-permanent and execution of various operations occurs at a number of sites within the plant.

de Altamer, (1) and Page (2) describe the welding station concept of heavy vessel fabrication at Breda Termomeccanica, which centres upon the Ansaldo N-SAW system. These facilities are similar to those supplied by Esab to the USSR for the Volga-Don Project (3).

5.3 Narrow Groove Weld Processes:

Processes which are being or could be used in heavy section narrow groove welding production are reviewed below with emphasis on welding 2¼ Cr-1Mo steel where a low hydrogen process and restricted heat input are necessary for sound welds of the specified properties.

5.3.1 Gas Tungsten Arc Welding (GTAW):

The GTAW process has not found general usage in heavy section welding although the quality of GTAW weld metal is high and has prompted its use in the fabrication of low alloy steel submersible vessels up to 100mm thick, (5)(6). One U.S. fabricator has used an automated hot wire GTAW process for horizontal welding during site replacement of a steam generator circumferential seam (7). The process involves oscillation to ensure side wall fusion which together with porosity are the main concerns with GTAW heavy section welds.

Deposition rate for the process is low (1 kgm/hr.) and although productivity can be improved by using the hot wire process (2 kgm/hr.) or multiple heads, the literature and in-plant data indicate limited application to heavy section welding. The lack of past experience with GTAW in pressure vessel fabrication implies a lengthy learning period of operator and supervisor training prior to production.

The process offers advantages in depositing low hydrogen weld metal at low heat inputs but data to show that GTAW weldments in 2¼ Cr-1Mo meet the specified properties is not available.

One distinct set back to the use of GTAW is that filler metals commercially available are designed for GMAW with CO_2 shielding and high quality special formulations are required to satisfy both process and toughness requirements. Filler metal selection is often necessary to ensure acceptable wetting characteristics, a condition that is of paramount importance to a narrow groove joint.

Joint tracking systems are commercially available for GTAW welding and are based upon the arc characteristics which allows instantaneous corrections to torch location. The use of the process produces demands on production such that weld joints need to be precision machined and joint fit-up must match the same tolerances.

5.3.2 Gas Metal Arc Welding (GMAW):

In Japan, GMAW has received the most attention for narrow groove welding in heavy sections but no new processes are indicated. The Kobe twist wire process and the Babcock-Hitachi formed wire process have both been commercially available since 1979 and feature arc oscillation to overcome the main process weakness - lack of side wall fusion. In North America, GMAW has not found favor for pressure vessel fabrication although the Dimetrics' Gold Track system has been used by Rockwell International to weld vessel seams without rotation. As with GTAW, a considerable learning period is to be expected prior to production welding.

Intermediate deposition rates are offered (2 kgm/hr.) by depositing one layer per pass and productivity is improved by the use of multiple heads. Provided adequate gas coverage is maintained the low hydrogen potential would encourage the use of GMAW for welding 2¼ Cr-1Mo steel.

With the introduction of an oscillating arc the process groove width tolerances are relaxed and fit-up of the joint is not as demanding as for GTAW. Guidance systems are available for GMAW welding although the use of an oscillated arc poses problems with arc based automation. A serious practical problem with N-GMAW has been the arc instability caused by magnetic fields within heavy section weldments.

5.3.3 Flux Cored Arc Welding (FCAW):

The use of FCAW in pressure vessel production has been intermittently evaluated with unfavourable results. Although the process offers improved deposition rates compared to GMAW, lack of fusion defects are accompanied by porosity etc., arising from inconsistent flux distribution within the filler metal. Selection of consumables to confirm weldability and properties renders FCAW unattractive for narrow groove welding. Data from one manufacturer (27) has suggested that FCAW materials may not attain the required temper embrittlement resistance. FCAW is not considered a low hydrogen process unless the sheath is of a welded construction. The welding fumes are considered a health hazard which requires the use of fume extraction equipment at the welding head.

5.3.4 Submerged Arc Welding (SAW):

SAW is the most accepted process for pressure vessel construction with a long history of successful heavy section weldments made to ASME requirements. Operator training and learning is minimized and acceptable deposition rates (6 kgm/hr.) without excessive heat input have been shown in conventional grooves to produce acceptable properties by attention to consumable selection and weld parameters.

Flux formulation together with a two pass per layer approach has solved the slag detachability problem and the literature indicates that in Europe and Japan, N-SAW is gaining favour. The high hydrogen potential of SAW is aggravated by the need to use agglomerated fluxes to attain weld metal toughness. Flux conditioning is necessary to prevent moisture absorption but this requirement is built into a flux recovery/feeding system employed with an automated system.

The use of submerged arc welding allows the use of tactile guidance systems only and furthermore, weld metal quality is not confirmed visibly until slag removal has been completed. Nonetheless, process equipment is relatively simple, the absence of water cooled heads and primary/secondary gas supply allows the least degree of sophistication in weld head design.

5.3.5 Electroslag and Electrogas Welding (ESW; EGW):

Attempts have been made to develop EGW but in Babcock and Wilcox Company's experience weld quality is unacceptable in section sizes greater than 2 in. The application of ESW to pressure vessel manufacturer is well proven where longitudinal seams receive the greatest benefit from single pass welding in the vertical-up position.

The overall economies of the process have been set back by the need to normalize the coarse as-deposited weld zone but with hot rolled 2¼ Cr-1Mo plate shells, one heat treatment develops properties in both the base material and the weld zone. The process has limited applications to circumferential seams since run-on and run-off tabs represent unnecessary welding and fit-up times. Furthermore, quench and tempering of multiple ring sections is not practical.

The process offers for longitudinal seam welding very high deposition rates in flame cut weld preparations assembled to relatively loose tolerances. The main set back to the process is that setup of welding dams, etc., is critical to allow completion of the weld without a time consuming re-start procedure.

5.3.6 Electron-Beam Welding (EBW):

EBW is receiving considerable attention for pressure vessel welding to take advantage of the highest joint completion rate without filler metal additions. EBW equipment is commercially available but has restricted application to this program based upon the need to weld in the 2G position only, the need for extremely accurate joint configurations, sophisticated electronic oscillation requirements and high capital equipment costs.

5.3.7 Summary of Weld Processes:

A significant observation from the review is that whilst the literature includes studies of process parameters (12)(13) and one practical application of N-GMAW (14), details of new N-GMAW processes have not been described. At least two N-SAW systems from Europe have been reported and have been proven in production (1) (19) (3) with a third system (26) being developed for distribution in the USA. Recent developments in SAW flux formulation indicates that the slag detachability problem has been resolved and the use of N-SAW in pressure vessel construction represents only a refinement of proven technology compared to the training and learning periods posed by GMAW.

A questionnaire distributed by JIW/JWS to fabricators representing Japanese heavy industry to evaluate advantages/disadvantages of narrow groove welding revealed that narrow SAW is finding acceptance mainly in the pressure vessel industry and represents 32% of narrow groove applications; N-GMAW still represents 67% of narrow-groove application in pressure vessel fabrication (8). The most significant advantages and disadvantages of using N-SAW or N-MIG were summarized and shown in Figure 4 and necessary development work is identified in Figure 5. Whilst the comparison indicates that both processes offer similar advantages the salient feature of Figure 5 is that N-MIG is identified as requiring far more development work than the more recently introduced N-SAW.

5.4 Methods of Seam Tracking:

Development activities for torch guidance have been based upon the use of tactile or eddy current measurements of the groove; fluidic sensing of the joint sidewalls; electro-magnetic or electro-optic sensing and arc sensing devices. Mechanical methods with rugged simplicity offer cost effective solutions to joint tracking. Arc sensing devices have been the subject of extensive development in recent years and are currently in the forefront of guidance systems. Sensing devices based upon measuring arc characteristics are being developed for SAW but are not as yet commercially available. Fluidic sensing methods (9) require machined sidewalls, are extremely sensitive and have been used only in laboratory systems. Electro-optical sensing (10)(11) and computer vision are not applicable to an arc submerged in flux.

Seam tracking options for N-SAW are restricted to systems using:

(a) Tactile probes, e.g. Cyclomatic's Omni guide sensor, Ansaldo's 3S sensor and Esab's mechanical contactor system built into the HND weld head.

(b) Electro-magnetic sensors. Babcock and Wilcox Company are developing noncontacting probes which utilize eddy currents to sense the groove sidewall. The advantages of noncontacting probes are to allow a more rigid unit than is practical for a sensitive tactile probe.

Since commercially available guidance systems for submerged arc welding are based upon mechanical contactors there is no one system that will provide guidance from the weld root to the capping passes. When there is no longer a distinct weld groove edge to follow, an alternative guidance method is needed to complete the weld joint. This situation will still arise when eddy current probes are developed. A seam tracking system based upon the arc being the sensor would enable one system to be used throughout the complete operation.

The Cyclomatic system of joint tracking represents the general automatic feedback servo mechanism common to tactile systems, i.e. position is referred to as a reference, an input signal proportional to displacement generates an error signal which drives a motorized slide to correct the torch position to the required accuracy. The Omni-Guide system uses an electro-magnetic sensor which responds to probe tip movements by generating an analog signal that maintains the torch in the predetermined location.

The Ansaldo system also uses a tactile probe but is far more automated in its response mechanism (2); probe and hence torch location are compared to a pre-programmed position. The probe itself is not rugged a criticism also of the Cyclomatic probe.

The sidewall guidance employed by Esab is designed into the narrow groove welding head and features a rugged, pivoted sidewall contactor with ceramic tips. Mechanical displacements produce optical signals that are directly relayed to a micro-computer/cross slides without the analog to digital conversions required by the Ansaldo system.

5.5 Methods For Vertical Guidance:

5.5.1 Arc Sensing Methods (15)(16):

Consumable electrode welding processes require that a constant distance be maintained between electrode and work piece and power sources generally exhibit a slightly drooping or slowly rising characteristic. With constant wire feed rates a state of balance is maintained through the acceleration or de-acceleration of the burnoff rate and a self regulating arc length is maintained. Increases in arc length due to height variations cause an increase in welding current but the self regulating effect of the arc and power source are only partially effective in correcting the condition because the gradual changes in work piece to torch distance cause slow changes in arc distance. The weld current instead of arc length is thus used as the controlled variable to correct current disturbances. Since changes in distances between torch and work piece effect welding current, automated vertical torch position becomes a prerequisite for current control. The welding current is measured using a shunt, the signal is amplified and compared to an adjustable control value. The difference between instantaneous value and reference value is used to control the torch adjusting motors to correct the deviant current value. Process dependant current fluctuations (droplet detachment and transfer, weld pool movement etc.) produce irrelevant signals and are filtered to prevent false reaction of the control circuit.

The CRC Through-arc proximity control unit is the only commercially available means of maintaining torch height by sensing arc characteristics and would appear appropriate to N-SAW. The cross seam positioning unit manufactured by CRC also utilizes arc current to guide an MIG or SAW torch along the groove but requires an oscillating welding arc to sense sidewall location. A two coordinate tracking system sets all relative parameters (oscillation amplitude, frequency and separate dwell times at groove center and sidewalls). Two ideal values are selected one for each groove face and a lower value for groove center and are compared with actual values; with slow oscillation adjustments are effected before the next comparison is made. The system has not been demonstrated as applicable to a narrow groove format and may have limited application to a process which utilizes a two bead per layer philosophy. Babcock & Wilcox Company are developing with CRC the Through-arc height control for N-SAW with AC power sources.

5.5.2 Tactile Methods:

Electro-mechanical systems for torch height control use probes located as close as is practical to the welding arc; irregularities in groove contour produce tip displacement which activates servo motors to correct torch height. Such methods are criticized because of tip wear, fragility of contactor probe and because information which motivates torch correction requires a memory system to overcome the spacial separate of torch and probe. In the Esab system, vertical height is sensed by a probe separate from the sidewall sensing unit. A spring loaded roller detects groove variations close to the welding head and optical welding signals produce corrective actions via vertical cross slides. The Ansaldo height control is integral with the seam tracking probe and as such resembles the Cyclomatic sensor.

5.5.3 Vertical Guidance For N-SAW:

Vertical and sidewall control based upon arc characteristics is preferred for N-SAW. However, such systems are not commercially available and to utilize the CRC Through-arc for height control in preference to the system incorporated into the N-groove welding heads represents a complicated design change to prevent disturbing the balance of control functions. At present both joint tracking and height control options are limited for N-SAW to tactile measuring methods.

5.6 Narrow Groove Submerged Arc Welding:

5.6.1 Options for Joint Filling:

The one pass per layer concept of narrow groove welding has remained the accepted approach to N-GMAW in Japan where sidewall fusion effectiveness depends upon arc oscillation by the use of pre-shaped wire. A secondary benefit of arc oscillation or rotation has been to restrict the welding heat input.

The need to preform welding wire represents an unnecessary process variable or consumable cost extra although Babcock Power indicate development activity in the use of a Kobe twist wire in a N-SAW process (18). The option of voltage control introduces the need for relatively high heat input that in a general sense detracts from low temperature toughness. Welding two beads per layer is therefore preferred from both a practical standpoint and to allay metallurgical concerns.

A weld bead connecting one sidewall to the other presents a continuous coarse grain path across the joint and raises a concern over high temperature properties at least on a micro scale. A two bead per layer process interrupts the continuous coarse grain weld metal at each bead intersection.

Welding with single bead per layer requires precise control of welding variables to avoid bead cracking; groove preparation and set-up are more critical and torch guidance for a centreline location requires an adaptive control to accommodate variations in groove width (19)(20)(21).

Finally, the solution to slag detachability has been in the formulation of fluxes and by welding at alternative sidewalls (19)(20)(21).

5.6.2 Development of N-SAW Fluxes:

The Kawasaki NSA process (22) continues to use a one bead per layer approach to narrow gap welding, so that flux development work has applicability to an alternative sidewall welding approach. Correlation between observed slag detachability and softening temperatures, melting point and thermal contraction revealed that slags with little expansion due to transformation during cooling exhibit superior welding characteristics. Optimum groove shape is governed by deterioration in slag detachability and avoidance of hot cracks; as groove angle and root gap are increased, weldability improves. Although groove angle has the greatest affect, the optimum weld preparation is defined as 12mm and 3°.

Russian work (21) has compared various commercial fluxes for slag detachability in narrow groove welds made with both one bead and two beads per layer processes (groove width 18 to 28mm). Whilst slag detachability in the single bead approach in all instances was unacceptable, all tested fluxes (including Linde 80 and Linde 124) showed acceptable results in 100mm test plates welded with two beads per layer.

Tenaka (23) records welding parameters and properties of 2¼ Cr-1Mo joints welded by N-SAW with 3.2mm wire and Kobe MF200N flux by a combination of single bead and two bead per layers in a 126mm plate. Acceptable toughness after step cooling is recorded.

Hantsch et al (24)(25) have investigated the optimization of narrow groove filling with emphasis of microstructure controls; to compensate for fluctuations in gap width due to assembly tolerances, shrinkages, etc., MAN-GHH use a two bead per layer technique. For weld thicknesses over 300mm where root accessibility becomes problematic, a 3 bead per layer technique is advocated [see also (21)].

5.7 ELECTRO-SLAG WELDING FOR PRESSURE VESSELS

5.7.1 Economic Considerations:

Vrbensky et al(28) compiled a comprehensive comparison in 1970 of ESW and SAW for nuclear reactor pressure vessels and concluded that ESW was a suitable technology for heavy wall vessels and provided solutions to problems of steel quality, production and transportation posed by the demand for 5,000 mm dia. and 300 mm wall thickness vessels in the USSR.

The use of ESW offers direct positive economies in the form of high labour efficiency (200 - 300% higher than SAW), cost savings from lower filler metal and flux consumption, reduced weld preparation, preheat and intermediate stress relief time. Additionally indirect positive effects of using ESW were identified as lower incidence of defects and the corresponding simplification of NDE techniques. The economic advantages of ESW have also been quoted by Nichols (29) and for petrochemical upgrading vessels by Knight et al(30) who compared longitudinal seam welding with narrow groove processes.

The application of ESW to pressure vessel manufacture has been demonstrated feasible by both CBI(31) and Foster Wheeler(32) but large scale acceptance has been impeded by the need for normalizing for weld zone recrystallization and the distortion associated with high heat inputs which increase the weight of semi-finished products to allow corrective machining. For 2¼ Cr - 1 Mo, the need to heat treat the weld zone in hot formed shells is satisfied by the quench and tempering that develops plate properties.

5.7.2 Process Parameters:

Square edge preparations produced by conventional flame cutting are used for ESW without the need for removal of oxide, scale, hardened zones or minor blow backs that produce ripple in the plate edges. The kerf on the flame exit side is removed by local dressing to avoid lack of contact or fouling with the contact shoe and the plate surfaces are lightly ground to remove surface irregularities. Variation in plate thickness and forming tolerances require attention to restrict joint misalignment to 3 mm with standard articulated shoes otherwise adaptor shoes to match the fit up are required.(33)(28)

5.7.3 Welding Parameters:

Typical SAW wires with low deoxidizing elements (Mn, Si) in combination with fluxes which contain high proportions of SiO_2 and MnO produce a heterogeneous deoxidization process causing reduction in weld metal manganese and silicon. During the initial welding stages such reactions produce oxidation of iron to yield high soluble FeO contents. Basic chemical requirements for ESW welding are described in references 28, 34, 35.

Miyano(36) and Okumura(37) report that for quenched and tempered 2¼ Cr-1 Mo electroslag welds, 0.14% C and 0.85% Mn represents a compromise between tensile strength (hardenability) and toughness and that after step cooling an optimum range of Mn of 0.7 - 0.85% exists where FATT shows a minimum. Tensile strength was further increased by additions of titanium, niobium and vanadium but only vanadium additions produced favourable impact properties (to 0.02%V). Okumura also addressed the effect of welding procedure upon mechanical properties of ESW weld metal.

Noting that lack of fusion is one of the major set backs with ESW weldments, Frost(37) investigated the control of the process through control of heat input. The functional relations between process variables and weld integrity are described.

Serrano et al(39) have evaluated the potential of the ESW process to produce 2¼ Cr - 1 Mo welds without subsequent austenitization. Detailed weld zone metallography is reported and mechanical data show that P.W.H.T. at 760°C and 690°C improve toughness of weld metal. The authors advocate further trials using clean base plate (and supposedly pure filler metal) to establish that toughness levels required for petrochemical application can be attained.

Edwards and Frost(40) show that a high welding current is desirable from a thermal history standpoint for ESW of 2¼ Cr - 1 Mo; a high weld velocity, low exposure time to the heat flux from the slag bath and low total heat input to the parent plate are provided by high welding currents. For 100mm plate welds, a current in excess of 600 amps is required to ensure that cooling rates below the lower critical temperature are sufficient to miss the ferrite nose and ensure a fully bainitic structure with optimum toughness. The authors also have investigated in depth chemical changes during ESW and propose an electrochemical series to account for anodic and cathodic reactions.

Shackleton(41) records the results of a Welding Institute review; ESW is used for increased productivity and the only problem area is that of low weldment toughness (for as-welded joints). Culp(42) additionally identifies low yield strength, loss in ductility and limited fatigue data as problem areas with as-welded ES welds. Davenport et al(43) describes the incidence of micro cracks in ESW used for bridge construction; the hydrogen induced cracks are usually located in the pro eutectoid ferrite outlining prior austenite grain boundaries. An AISI-WRC project evaluated the influence of welding parameters upon the incidence of "ferrite vein cracking" in structural steel weldments and concluded that control over the occurrence was possible by the use of preheat/post heat, atmospheric control above the molten bath and the use of dried flux of moderated basicity. The incidence of hydrogen cracking in structural electroslag welds has been reviewed more recently by Konkol(44) and the use of an acidic flux, high slag depth, high silicon electrodes tend to eliminate grain boundary cracking. The review has not revealed information upon the formation of hydrogen cracks in ESW in 2¼ Cr - 1 Mo steel.

5.7.4 Process Development

The modern process of ESW involves the use of consumable guides which melt and add to the weld pool. A flux coated electrode wire has also been reported. The use of strip electrodes is advocated by Dilawari(46) to improve heat transfer characteristics from the slag to the base metal. Electrode melting is more efficient and a 30% energy saving can be realized.(45)

For section thicknesses above 50 mm a single guide tube is oscillated back and forth across the joint to distribute the heat uniformly or, multiple electrodes are used.(42) For pressure vessel welding both Esab AB and Ritchlin Manufacturing offer two or three guide welding heads which include oscillation and enable welding of wall thicknesses of 450 mm at 4.6m long.

Faster welding speeds, grain refinement, a more uniform weld metal composition and improved gas removal are the advantages proposed by Kompan(46) provided by the use of a longitudinal magnetic field during ESW.

Soviet researchers have evaluated welding procedures in which optimum cooling rates for the weld and heat affected zone can be predicted and controlled by the use of hydraulic spray devices. Application of high heat input ESW with controlled thermal cycles to production welds is reported.(47) (48)

5.7.5 SUMMARY

Electroslag weldments in 100mm thick 2¼ Cr-1Mo steel have been shown to exhibit acceptable ambient and elevated temperature tensile properties in both the stress-relieved and quench and temper condition. Charpy V-notch toughness levels at 0°C are high and provided high purity materials are used the attainment of 54 kJ at -30°C is promising in the stress-relieved, quench and temper, and STC condition.

The hydrogen damage reported in structural ES weldments has received considerable attention in the literature. Remedial actions appear to correct poor welding practices; since attention to consumables is normal practice for pressure vessel fabrication hydrogen cracking does not represent a concerning problem area.

Consumable guide welds in 203mm thick, 3m longitudinal seams does not permit the use of oscillated electrodes since control of wire placement becomes poor at guide lengths greater than 2m. Uniformity of groove penetration is accomplished by the use of a three wire system and attention to welding parameters.

The literature indicates that U.S. fabricators (C.B.I., Foster Wheeler) are successful in producing ESW for 2¼ Cr-1Mo pressure vessel subsequently austenitized, Dominion Bridge continues to use the process for light gauge construction and provides typical parameters for material thickness to 100mm. Welding parameters for heavy section weldments using a multiple electrode process are required and optimization would benefit Canadian fabricators.

5.8 SUMMARY OF LITERATURE REVIEW

Proven N-SAW systems have been identified from two European manufacturers - Ansaldo Spa in Italy and Esab AB in Sweden. The Kawasaki, K-NSA process offers a deep groove nozzle but mainly depends upon the company's flux formulation. Esab's equipment is identified as

the preferred welding system for circumferential seams since both head and guidance probe are integrated into a rugged design allowing ease of bead location control. The welding head is but one component of an overall welding centre concept. Service and parts are available in North America through ASEA Ltd. (distributor) and the equipment is designed for marketing, assembly and operation with a minimal learning period.

Electroslag welding has been identified as the preferred approach for longitudinal seams and equipment from Esab AB and Richlin Engineering Ltd. represents state of the art technology.

2¼ Cr - 1 Mo plate and forging material can be welded by G.M.A.W., S.A.W. or E.S.W. with adequate toughness in the weld metal and heat affected zone provided due attention is paid to filler metal formulation, flux purity, heat input (cooling rate) and suitable post weld heat treatment cycles.

6.0 RECENT DEVELOPMENTS IN 2¼ Cr - 1 Mo STEEL FOR PRESSURE VESSELS

6.1 Literature Review

A literature review to search developments in 2¼ Cr - 1 Mo wrought material and weld consumables used Compendex, Weldasearch Metadex and DOE Energy information retrieval systems. A bibliography of literature reviewed is listed in Section 8 (49-88).

6.2 Background

The 2¼ Cr - 1 Mo steel has been the favoured material of construction for large, heavy-wall pressure vessels for the petrochemical industry. The basis for material selection is high temperature properties, resistance to hydrogen degradation and creep embrittlement.

Temper embrittlement occurs in 2¼ Cr - 1 Mo steel when exposed to the temperature range is 370°C to 600°C which encompasses both PWHT temperatures employed during fabrication and operating service temperatures.

Initial development effort to minimize temper embrittlement was aimed at heavy section plates and forgings. Rapid cooling or quenching to develop the desired bainitic microstructure and control of impurities (P, Sb, Sn and As) and other related elements (Mn and Si) resulted in good control of temper embrittlement. Producers data (58-6) describe 2¼ Cr - 1 Mo material up to 510mm in thickness which exhibit impact energies of 54J at -40 °C maximum after step-cooling.

The development of welding consumables up to 1979 did not keep pace with the work on wrought products. Subsequently, the weld material became the "weak link" for petrochemical vessels.

6.3 Recent Developments:

The literature review indicates considerable development of weld consumables for 2¼ Cr-1Mo steel (49, 63-74) mainly in the area of weld metal impurity reduction or control. Fracture mechanics characterization of 2¼ Cr - 1 Mo base metal and weld metal also received attention (49, 75-79). A specific area for review was the ability of SMAW, SAW, MIG and ESW consumables to attain 54J at -40°C after PWHT and a 54J TTr at -20°C after step cooling. SAW welds, both single and tandem arc, and SMAW welds show such resistance (63, 66, 68, 70, 72, 74, 80). MIG welds appear to have adequate resistance to temper embrittlement (64, 66) and electroslag welds produce a coarse grain weld metal structure which must be subsequently refined by heat treatment (70).

Predictive methods for temper embrittlement assessment of 2¼ Cr-1 Mo steels include the Bruscato factor (51) and the Japanese derived J-factor (50). These relationships are empirically developed from experimental data and exhibit a considerable scatter. Material selection or process evaluation should be made on the basis of mechanical properties of material after PWHT and a step cooling treatment to evaluate temper embrittlement.

Other relationships deal with shifts in the 54J Charpy impact transition temperature due to embrittlement. A widely used relationship adds the transition temperature shift due to embrittlement $\triangle$ TTr54 to the 54J transition temperature and limits this total value to a maximum number (55, 72, 80, 82).

$TTr + F \triangle TTr54 \leq$ max value, where F = 1.5 to 3.5

Several investigators have examined embrittlement due to isothermal exposures and service exposures as well as step cooling. The results of these studies indicate service embrittlement in the form of a transition temperature shift seems to be related to the $\triangle$ TTr54 after step cooling. In one case the service embrittlement $\triangle$ TTr54 was three times the $\triangle$ TTr54 for step cooling (70).

Research has shown that manganese and silicon promotes temper embrittlement; however, these elements are required in the 2¼ Cr -1 Mo steel to maintain good fabrication characteristics and mechanical properties. Manganese and carbon are needed to develop a bainitic microstructure and thus good mechanical properties at the center of heavy, heat treated sections (66). Minimum levels of manganese are also needed for good weldability (67). Silicon is needed to maintain room temperature and elevated temperature strength. Low-silicon 2¼ Cr - 1 Mo forgings and low-silicon forgings with vanadium, titanium and boron additions have exhibited room and elevated temperature strength levels in excess of the ASME Section VIII Division 2 requirements (85, 86).

Alloy development work for both wrought products and weld metals indicates vanadium additions of about 0.05% reduce temper embrittlement susceptibility after step cooling (71, 73). Additions of rare earth metals also appear to reduce temper embrittlement susceptibility in both plate and weld metal (49, 76, 79). Grain size control in 2¼ Cr-1 Mo plate through the use of titanium or aluminum has been found to reduce temper embrittlement susceptibility (76). However, titanium used with vanadium appears to increase the susceptibility of 2¼ Cr-1 Mo weld metal (73). Finer prior austenitic grain size not only increases the initial Charpy impact energy (before temper embrittlement), but also increases the total grain boundary area. Thus, the average concentration of impurities at the grain boundaries is lower and the effect of temper embrittlement is reduced.

There is some evidence that small additions of nickel up to 0.20% improve impact energy after P.W.H.T. (72). Other work involving additions of 0.5% nickel and 0.5% manganese to 2¼ Cr-1Mo steel appears to improve tensile and impact properties for certain heat treatments without increasing temper embrittlement susceptibility (71). Major additions of nickel (2%-4%) to low alloy steels greatly increases temper embrittlement susceptibility (76).

Recent development of welding consumables has addressed fabrication problems such as hydrogen cracking, transverse weld cracking and reheat cracking. Investigation has revealed such welding problems are related that to high residual stresses and/or high hydrogen contents (87, 88) and shows that the use of low hydrogen consumables greatly reduce the incidence of weld cracking. High basicity, agglomerated fluxes or coatings are very effective in reducing cracking as well as contributing to desirable weld metal impact properties after temper embrittlement (63).

Stress relieving has been shown to reduce weld metal strength (59, 88) and may increase the impact transition temperatures if excessive stress relieving is employed (88). Intermediate stress relieving is used to avoid weld cracking during fabrication through removal of hydrogen. It has also been shown that the lower stress relieving temperatures will outgass hydrogen from the weld metal and avoid hydrogen induced cracking (88). Low temperature post weld heat treatments would then lessen the reduction of strength after stress relieving.

Fabrication variables such as heat input, multiple vs. single beads per pass and single vs. tandem arc, when combined with weld metal chemistry variables create a very large matrix which has not been completely addressed. The information published to date suggests that heat input should be kept to practical low values and that multiple beads per pass in narrow groove welding produces good impact properties in the weld metal and enhances sidewall penetration (67). Tandem arc wire welds with low heat inputs have been produced exhibiting good impact properties after step cooling.

Fracture toughness data has been studied to permit estimation of critical flaw sizes and remaining life of reactor vessels. (77, 76, 84). Operating parameters such as start-up and shutdown can be affected by reduced fracture toughness (83).

Fracture toughness has been evaluated in the presence of hydrogen and hydrogen sulphide. (49, 75, 76, 78, 84). In general, lower thresholds for hydrogen sulphide or hydrogen-assisted cracking occur at higher strength levels.

6.4 SUMMARY

6.4.1 Tramp elements which promote temper embrittlement in weld metal should be kept below maximum levels, e.g.phosphorous - 0.012%, tin - 0.005%, arsenic - 0.010% and antimony - 0.005%. Silicon level may be less than 0.20% and manganese should be 0.45% to 0.70%.

Attention should be focussed on additions of nickel (up to 0.20%), vanadium (up to 0.05%) and rare earth metals to 2¼ Cr-1Mo steel for increased resistance to temper embrittlement. Additions of titanium or aluminum for control or prior austentite grain size also contribute to increased embrittlement resistance.

6.4.2 The fracture mechanics properties of 2¼ Cr-1Mo plate, forgings and weldments need defining in the as-fabricated and temper embrittled conditions in hydrogen environments. This information will support fracture mechanics analyses of reactor vessels and other equipment to predict limiting stresses, critical flaw sizes, required material toughness properties and remaining plant life.

7.0 PURCHASE AND ASSEMBLY OF WELDING EQUIPMENT

7.1 Purchase of Welding Equipment

7.1.1 A detailed review of the Esab EHD system considered those items required for reactor vessel fabrication but components were selected primarily to develop weld procedures recognizing that existing plant would support the welding head and vessel rotation. The assembly of component parts, support mechanisms and additional items was addressed with the following action items. The individual equipment components ordered are summarized below.

Item 1 - One narrow gap welding head, type HNG (E80SA-EHD).

Item 2 - One control cabinet for welding parameters, joint tracking and bead overlap. (E80 SA-Type CB/CC4).

Item 3 - One set of slide adaptors and insulating bushings. (E80 SA-Type A4).

Item 4 - One set of motorized horizontal and vertical ball screw slides. (E80 SA Type S4/S5).

Item 5 - One pulse generator for circumferential seam revolution monitoring. (E80 SA-EHD Option TG).

Item 6 - One free standing flux feeding/recovery system. (E80 SA-EHD Type FFS).

Item 7 - One DC power source, type LAD, 1450 amp, 100% duty cycle.

Item 8 - Dimensional and detail drawings for all the main components were ordered as reproducible prints to allow spacial arrangement for all components. Schematic and assembly diagrams were ordered to show standard electrical ratings or electrical trade descriptions for all component parts. All electrical equipment was ordered to be supplied with Ontario Hydro approval and for a 575 V-3 Phase - 60 HZ supply. Three copies of the operation and maintenance manuals were ordered to include an illustrated parts list showing all components identified to the manufacturers part numbers. A recommended spare parts list was also order for the welding head, flux feed system, power source and control cabinet.

Schematic diagram of the system components is shown in Figure 6.

7.1.2 The welding head and control cabinet are designed to operate with either a manipulator or gantry. Vessel manufacturer would utilize existing manipulators to support the welding head and accordingly a surplus column and boom would be made available for the laboratory stages of evaluation and test plate welding. An adaptor plate to connect the slides to the boom and a multi-pivot arm to connect the boom to the control cabinet were fabricated in-plant.

7.1.3 The flux handling and recovery system (FFS) is pneumatically operated requiring compressed air feed to the pressure tank to be filtered and dried. As an alternative to purchasing the ESAB air drying unit, a Pall fiber filter unit was to be installed ahead of the pressure tank reservoir.

7.1.4 Two HNG welding head options were considered. The pulse generator unit is designed for continuous circumferential seam welding. Vessel rotation is monitored and the change of bead location/overlap length is controlled at preset increments. The unit could be demonstrated during the welding of flat test plates by using the manipulator boom travel to index bead crossover from alternate sidewalls. The pulse generator was identified as a desirable option since the system would be primarily used for circumferential seam welding. The second option for seam welding is the vessel edge sensing device which guides the welding head during the final weld passes. The adjacent circumferential seam is used to index this mechanism. Demonstration of this operation during flat plate welding was considered impractical and visual control was elected for the final passes.

7.1.5. Neither the MRS roller beds nor programmable control units were necessary to develop weld procedures using flat plates. Existing plant includes rotating devices with anti-drift features. Both options were considered attractive for vessel fabrication but outside the scope of supply for the current program.

7.1.6 The standard ammeter supplied with the control cabinet has a full range of 1500 amp. In order to read more accurately within the range of 450 to 750 amp a smaller unit and corresponding shunt were ordered to replace standard equipment.

7.2 Assembly of Equipment:

7.2.1 A 4m x 4m manipulator was made available for laboratory test weld equipped with Boston gear reducers, controllers and a tachometer feedback unit.

7.2.2 Delivery of the purchased components was made on schedule with no damage noted during uncrating and inspection. Figure 7 shows a general arrangement of the welding system. Figure 8 shows the detailed items of the welding head. Electrical connection of component parts was performed by ESAB service engineers who also connected the pulse generator to the manipulator boom to operate the head travel counting mechanism (Figure 9).

7.3 Commissioning the System

7.3.1 Initial performance testing of the welding, guidance and control systems was conducted using a nominal 19mm groove with 2° sidewalls in a 2m long x 50mm thick carbon steel plate assembly. Test welds were made with the assembly skewed from the welding direction and raised at one end to demonstrate the guidance system function. Crossover of the bead to alternate sidewalls confirm the pulse generator/indexing mechanism and with conventional flux (Linde 124) and 4mm wire, the flux feed and wire drive mechanisms were shown acceptable.

7.4 SUMMARY

The Esab HNG welding system has been ordered, received on schedule and erected onto a laboratory manipulator. All components have been demonstrated and malfunctions rectified by service engineers from the manufacturer. Support equipment has been manufactured and modified after welding trials indicated deficiencies. Weld parameter monitoring devices have been calibrated and the system was used without further modification to complete the weld procedure development.

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TABLE 1 - DESCRIPTION OF REACTOR VESSEL

GENERAL:

Overall Length:	34 m
Shell Diameter:	4.3 m
Shell Thickness:	205 mm
Tangent Length:	21 m
Hemispherical Head Thickness:	105 mm

FABRICATION & DESIGN CODE:

ASME Boiler and Pressure Vessel Code Section VIII, Div. 1 (Lethal Service).
All pressure retaining welds to be RT, UT and MT inspected after final PWHT.

Hydrotest: 1½ x design pressure

OPERATING CONDITIONS:

Nominal 17MPa at 480°C

MATERIALS:

Shell & Heads: ASME SA 387, GR22, Cl.2 or SA 335, F22.

Nozzles: Integrally reinforced main nozzles, ASME SA336, F22

Cladding: 5mm thick

MATERIAL REQUIREMENTS:

	Room Temperature	480°C
Tensile Strength, ¼t:	515-690 MPa	352 MPa min
Yield Strength, ¼t:	420 MPa min.	224 MPa min.

Charpy Impact Energy:

Base Metal, ¼t	54J at -40°C after PWHT 54J TTr -40°C or less after STC.
Weld Metal, ¼t	54J at -40°C after PWHT 54J TTr -29°C or less after STC.
Hardness	225 BHN max. after PWHT

TABLE 2

MANUFACTURING COST COMPARISON FOR CIRCUMFERENTIAL WELDING

	TANDEM ASAW D-GROOVE	AC-ASAW D-GROOVE	D-GMAW (D-B) D-GROOVE	D-SAW (ESAB) D-GROOVE	D-ASAW (ESAB) SINGLE SIDE WELD
M/C Weld Prep	30h	30h	35h	35h	25h
MT Weld Prep	10h	10h	10h	10h	15h
Fit & Align Weld Prep.	45h	45h	55h	55h	65h
Set Up for Welding	10h	10h	10h	10h	10h
Preheat to 205°C	10h	10h	10h	10h	10h
Weld 1st Side	55h	40h	65h	45h	135h
ISI	25h	25h	25h	25h	25h
Prepare Root	35h	35h	35h	35h	15h
MT Root	10h	10h	10h	10h	10h
Preheat to 205°C	10h	10h	10h	10h	—
Set Up for Welding	10h	10h	10h	10h	—
Weld 2nd Side	85h	115h	130h	95h	—
ISI	25h	25h	25h	25h	—
TOTAL	360h	375h	430h	375h	310h
Groove Section mm²	2775 I.D. 7080 O.D.	1870 I.D. 4905 O.D.	1100 I.D. 2130 O.D.	1250 I.D. 2520 I.D.	3725
Weld Parameters	3.2mm dia.wire 500A-35V-760mm/min.RP 550A-36-760mm/min.AC	4mm dia.wire 550A-32V-510mm/min.AC	1.2mm dia.wire 280A-29V-230mm/min.RP	4mm dia.wire 550A-32V-510mm/min.RP	4mm dia.wire 550A-32V-510mm/min.RP
Deposition Rate kgm/hr	5.4 I.D. 8.2 O.D.	4.5	1.8	5.8	5.8
Joint Fill Rate mm/hr	231 I.D. 157 O.D.	315 I.D. 117 O.D.	19.8 I.D. 104 O.D.	274 I.D. 142 O.D.	96.5
Welding Time	53h I.D. 83h O.D.	39h I.D. 112h O.D.	62h I.D. 125h O.D.	45h I.D. 92h O.D.	134h I.D.
Wt. of Wire, Kgm	1152	792	385	445	445
Wt. of Flux, Kgm	1440	990	—	370	576
Vol. of Ar L	—	—	500,000	—	—
Vol of CO_2, L	—	—	125,000	—	—
Cost of Operator/ Seam/($)	5840	6040	7320	5480	5480
Cost of Wire/Seam ($)	6035	4145	2340	2330	2330
Cost of Flux/Seam ($)	5360	3680	—	2110	2110
Cost of Argon/Seam($)	—	—	1550	—	
Total Cost/Seam ($)	17235	13865	11965	9920	9920
Sub-Total/Vessel (7 Seams) ($)	120645	97055	83755	69440	69440
Add Inc.vs-Set Up etc.($)	—	—	4200	4200	12600
Total/Vessel ($)	120645	97055	87955	73650	56850
Cost Reduction ($) Relative to Tandem ASAW	0	23590 (19.7 percent)	32690 (27.1 percent)	47005 (38.9 percent)	63805 (52.8 percent)

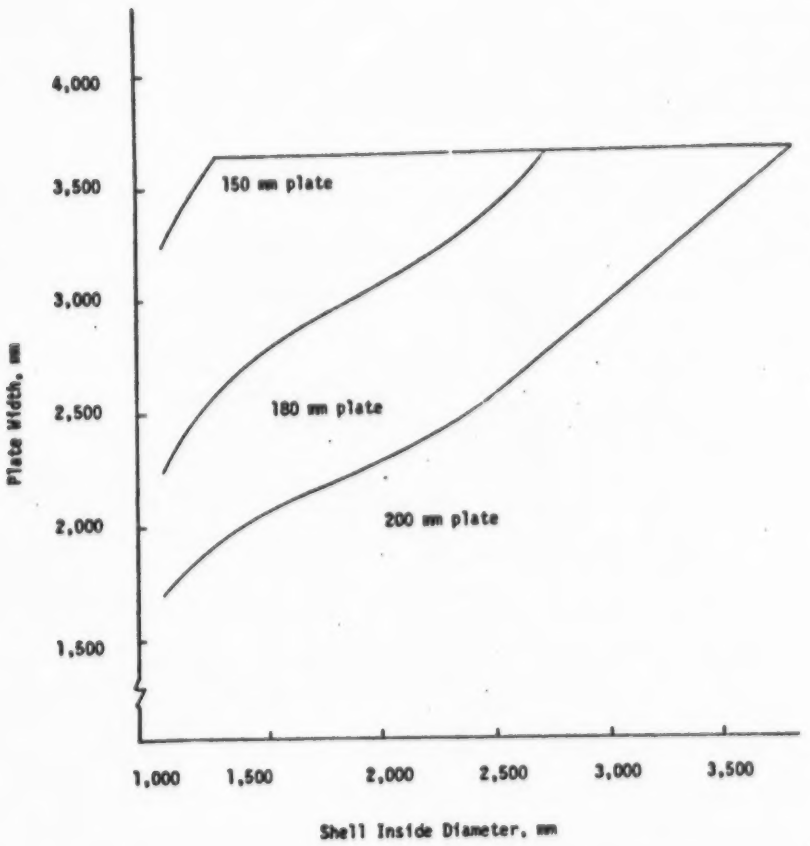

FIGURE 1: Relationship of plate width and shell diameter to thickness during hot rolling of high strength steel plates.

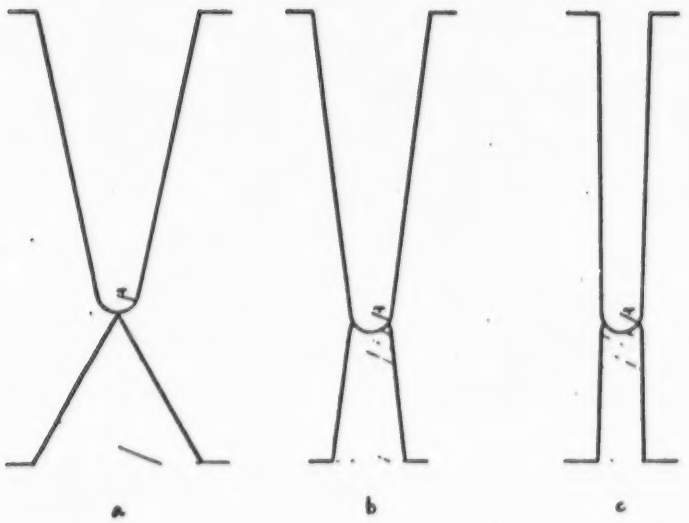

FIGURE 2 Comparison of Weld Preparation Details

(a) Conventional tandem ASAW
(b) AC N-SAW
(c) Esab N-SAW

r = 9.5 mm

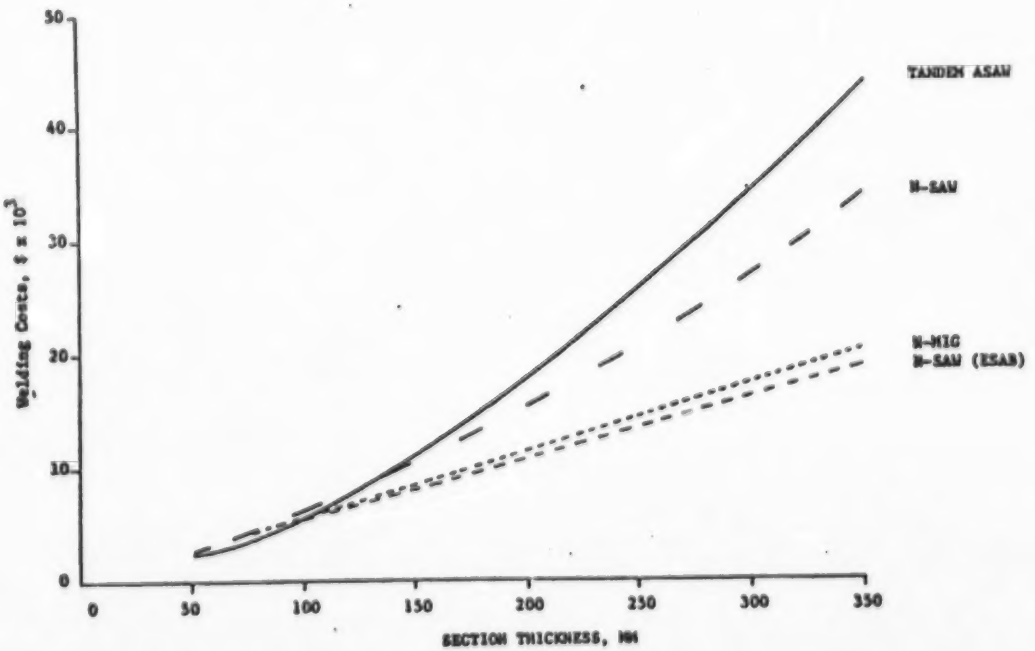

FIGURE 3 Comparison of Welding Costs for increasing joint thickness for various welding processes.

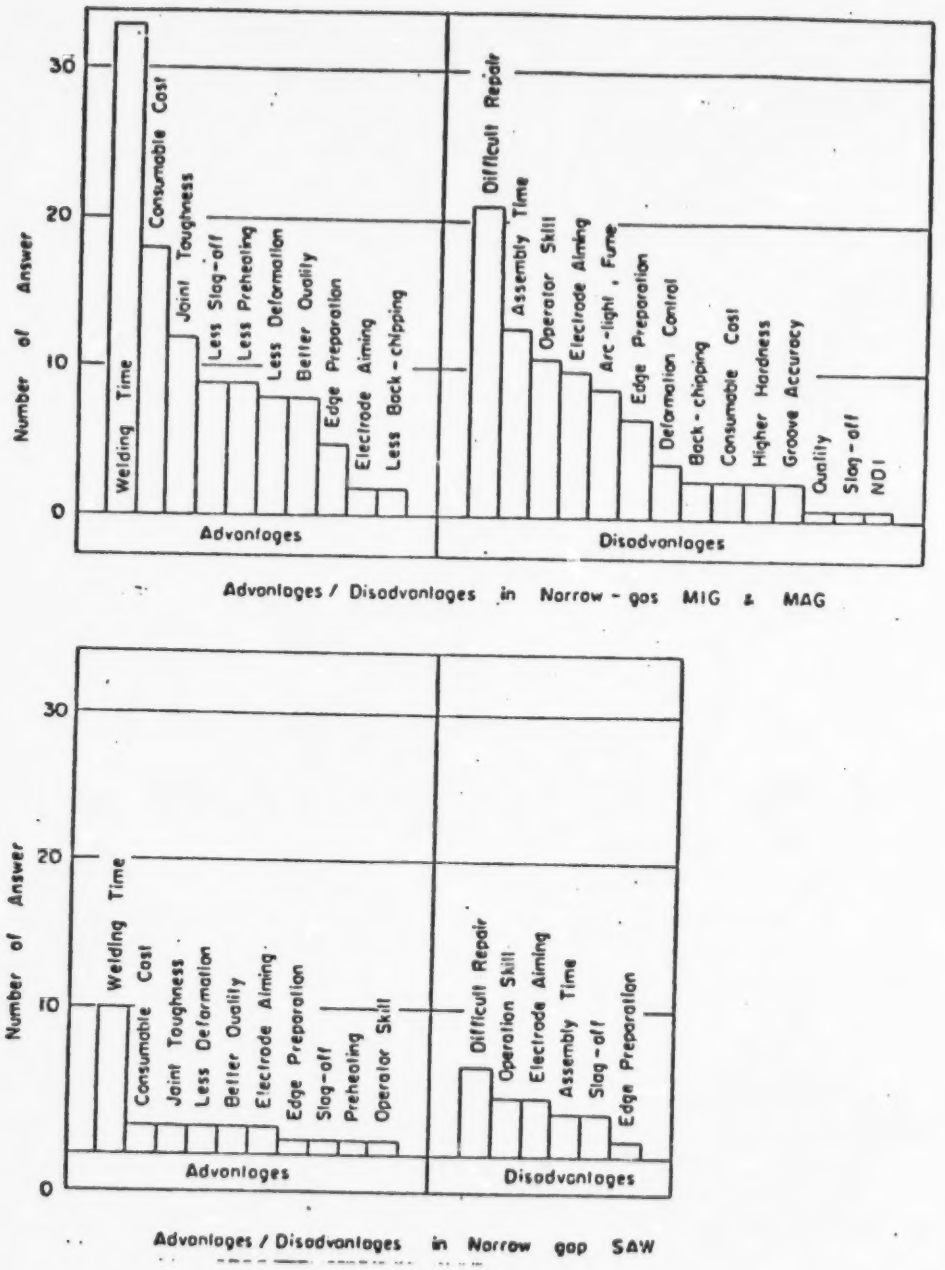

FIGURE 4 - Results of a questionnaire submitted to Japanese fabricators indicating advantages/disadvantages of narrow gap welding processes (8).

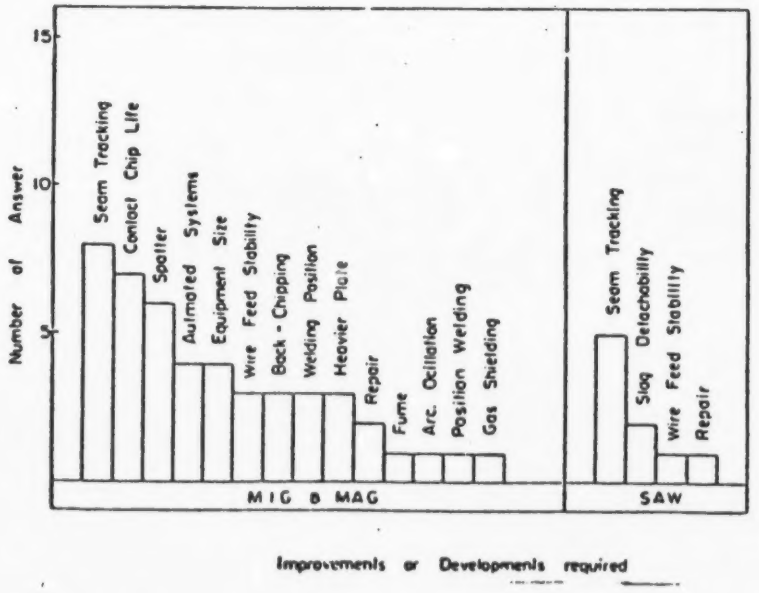

FIGURE 5 - Results of a questionnaire submitted to Japanese fabricators indicating areas of further development/improvements needed for narrow groove welding processes (8).

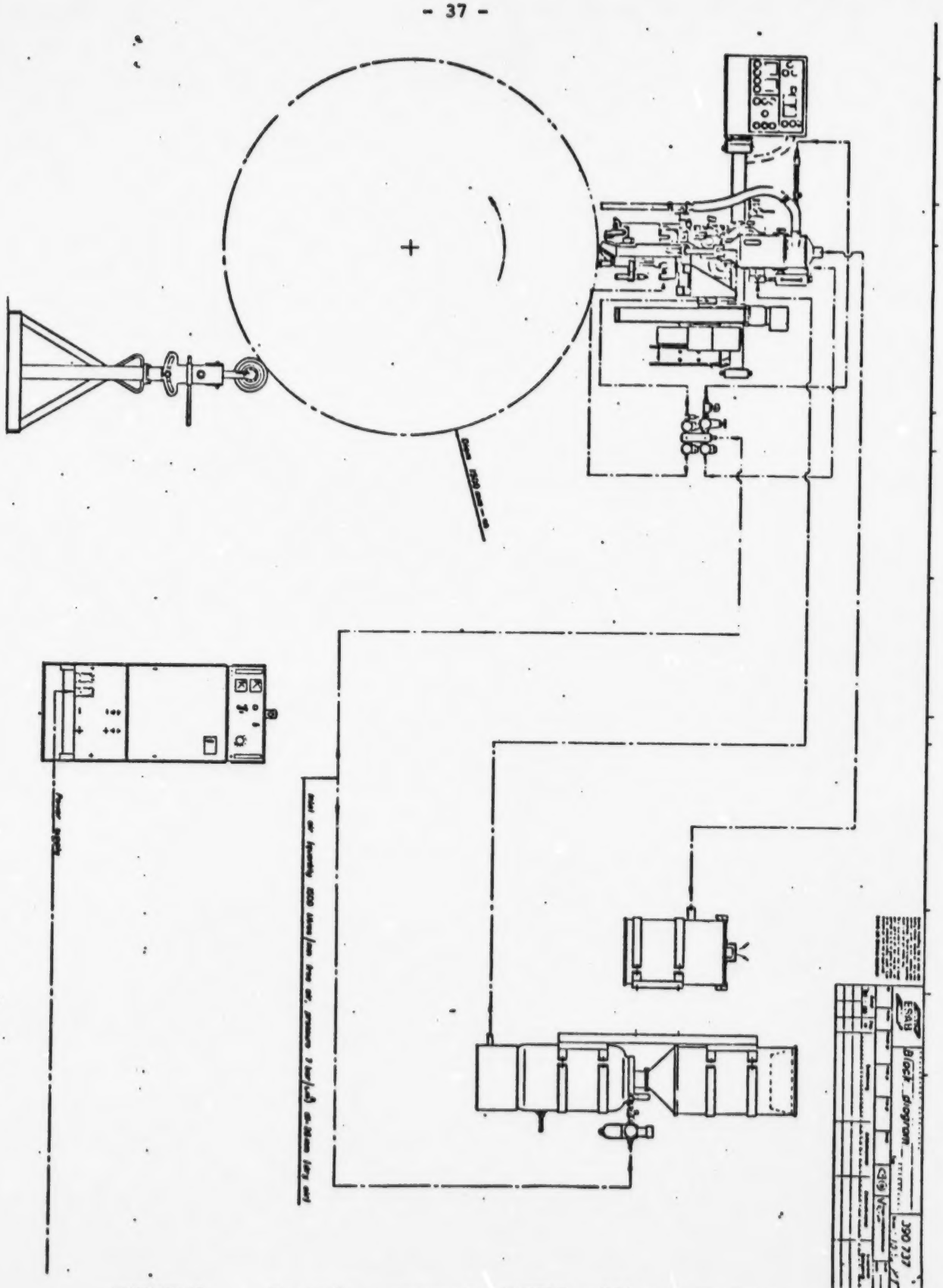

FIGURE 6 General arrangement of ESAB welding components.

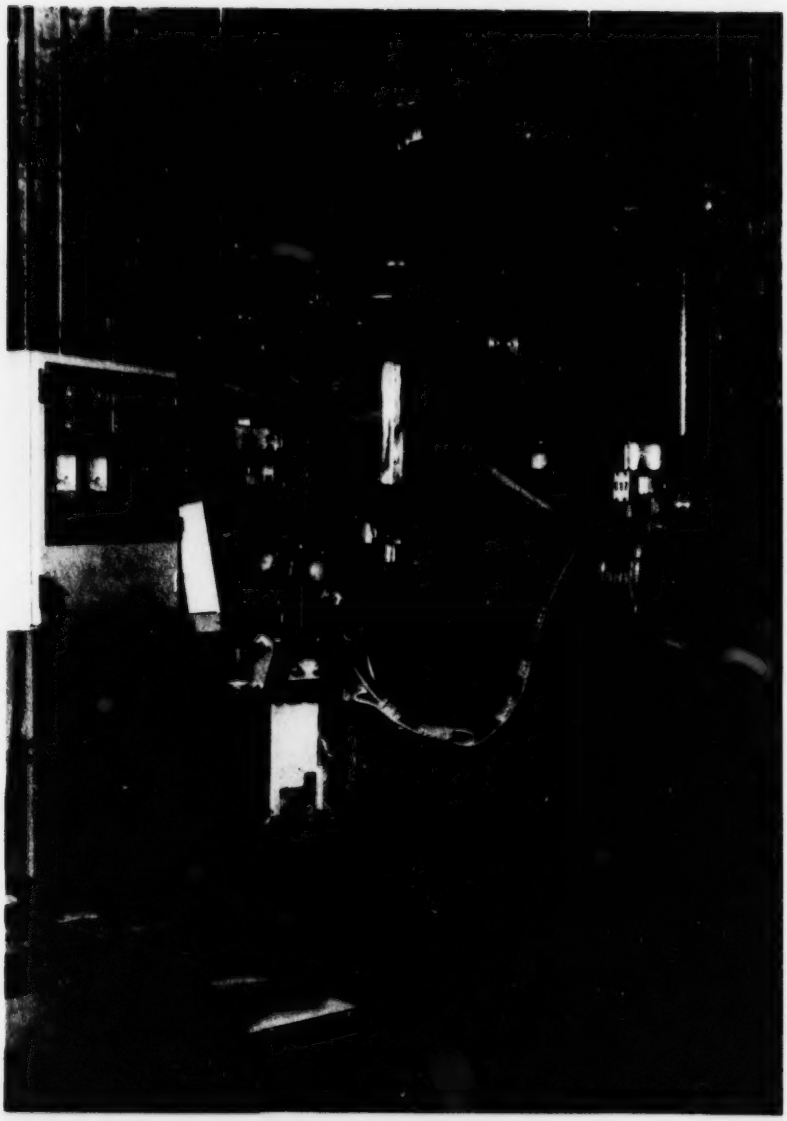

FIGURE 27 View showing general arrangement of narrow groove welding system.

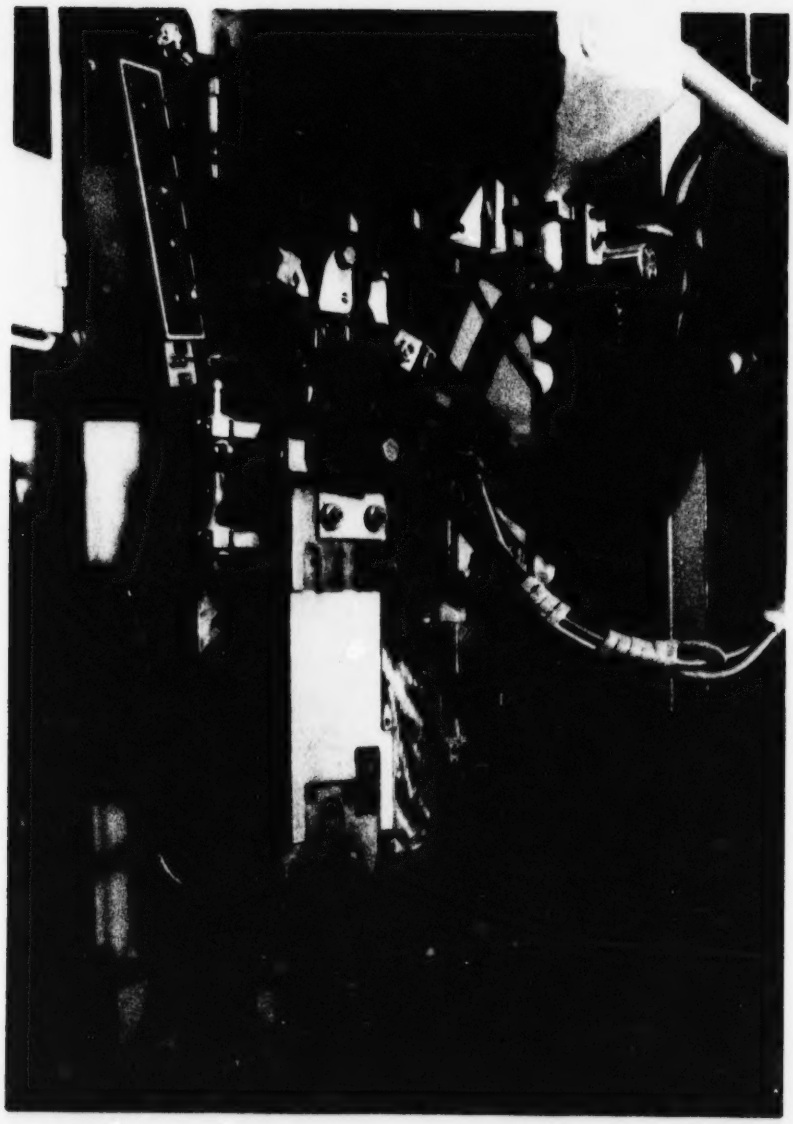

FIGURE 28 View showing detail of welding head.

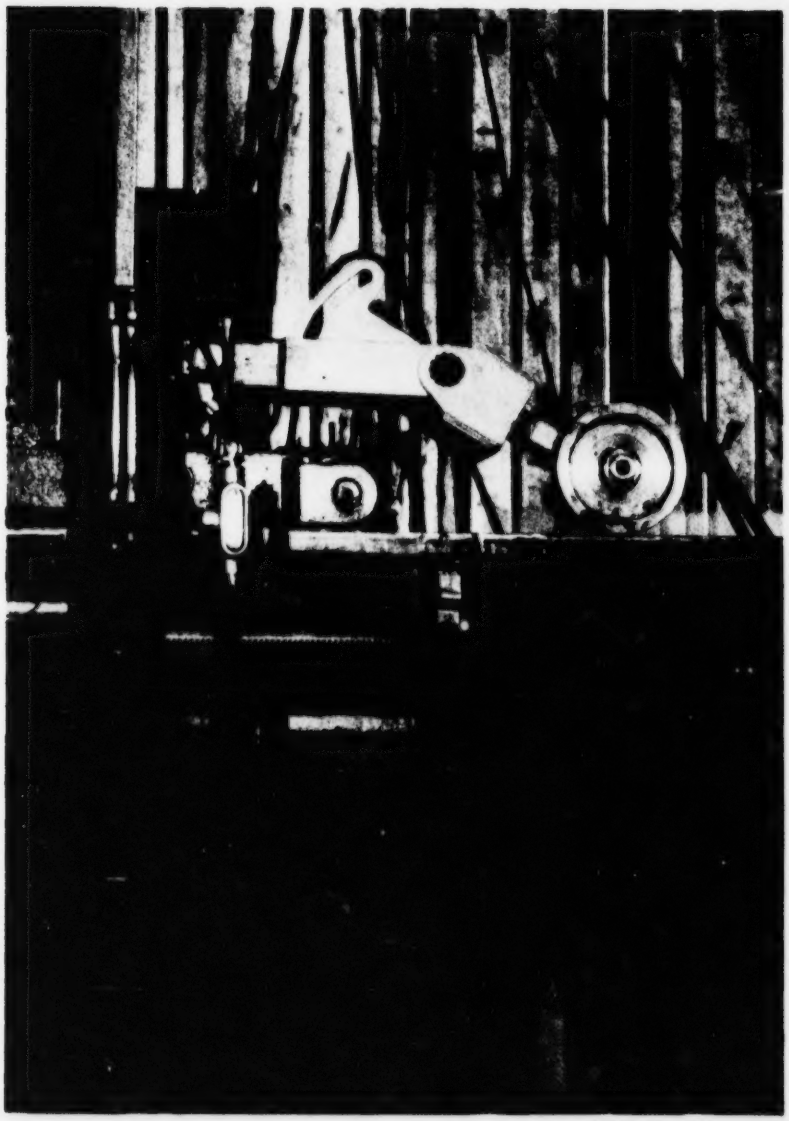

FIGURE 29 View showing pulse generator installation on manipulator.